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Editorial: Our changing cryosphere: understanding its dynamics, hazards, and implications for water security

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Editorial on the Research Topic
Our changing cryosphere: understanding its dynamics, hazards, and implications for water security

The Earth's cryosphere, comprising glaciers, ice caps, seasonal snow cover permafrost, and glacial lakes, represents a key component of the Earth system, deeply intertwined with climatic, hydrological, and ecological processes. It plays a central role in regulating the energy balance, sustaining water supply systems, and supporting biodiversity, particularly in high-mountain and polar regions (Hock et al., 2019). Meltwater from seasonal snowpacks and glaciers greatly influences downstream river flows in snow and glacier-fed watersheds, supplying water for hydropower, agriculture, ecosystems, and domestic needs (Immerzeel et al., 2020; Azam et al., 2021). However, the cryosphere is changing rapidly and dramatically as a result of rising global temperatures. There is currently ample evidence of glacier recession, permafrost degradation, decreased snow cover, and the growing number of moraine-dammed glacial lakes in cryosphere-dominated regions (Zemp et al., 2015; Bolch et al., 2019). These changes are leading to a range of interlinked impacts, including shifts in the timing and magnitude of meltwater discharge, changes in river hydrology and water chemistry and a rise in cryospheric hazards like rock-ice avalanches, Glacial Lake Outburst Floods (GLOFs), and thermokarst processes (Harrison et al., 2018; Emmer et al., 2022; Sattar et al., 2025). These growing hazards have been shown to pose substantial risks to lives, livelihoods, and critical infrastructure in several high mountain regions, whereas the shifting availability of water resources may further challenge the resilience of some mountain communities—particularly those already facing demographic pressures, land-use changes, and limited adaptive capacity (Ahmed, 2025). The impact of cryosphere-climate interactions on hydrology, hazard dynamics, and long-term water security is still not well understood scientifically in many regions, particularly in data-scarce mountain environments such as the Himalayas and the Tibetan Plateau.

To address these pressing scientific and societal challenges, this Research Topic (RT) titled *"Our changing cryosphere—understanding its dynamics, hazards, and implications for water security"* was conceived with the aim of improving our knowledge of cryosphere processes and their implications through interdisciplinary approaches. The RT mainly focused on advancing our understanding of cryosphere–hydrosphere–climate interactions, evaluating cryospheric hazards and risk reduction strategies, improving hydrological and thermal models for glacierized environments, and supporting sustainable water management in regions reliant on seasonal snow and ice melt.

The contributions submitted under this RT cover important facets of the evolving cryosphere and include from a variety of approaches and geographical regions. These studies offer new insights into how physical, environmental, and climatic factors collectively shape cryospheric processes and their downstream implications. Examples include modeling the thickness of debris on Himalayan glaciers, assessing groundwater recharge delays caused by seasonally frozen ground in the Tibetan Plateau, and examining hydrochemical shifts in Alaskan glacial rivers as well as isotopic variability in snow and glacier melt in Indian catchments. In the following sections, we concisely summarize the original research articles published under this Research Topic and reflect on the key findings, scientific contributions, and implications of each study.

The first paper by Ali et al. investigates supraglacial debris thickness on the Hoksar Glacier in the Kashmir Himalaya using empirical and thermal resistance approaches. The presence of debris on glacier surfaces has a profound effect on the thermal regime and melt dynamics; hence, accurate debris thickness estimation is essential for hydrological modeling. The study utilizes thermal remote sensing data from Landsat OLI and AST08 along with ERA5 reanalysis datasets. An empirical relationship was developed between field-measured debris thickness and satellite-derived surface temperature, and a thermal resistance method was applied using an energy balance model. The empirical approach underestimated debris thickness by 12–28%, whereas the thermal resistance method showed closer alignment with field data (deviation ∼11%). Correlation coefficients for temperature ranged from $r = 0.88–0.90$ ($p < 0.001$) for both datasets. The study concludes that thermal resistance methods can reliably estimate debris thickness without intensive field input and can be applied across heavily debris-covered glaciers globally. This contributes significantly to improving glacier melt estimation and forecasting water availability from debris-covered glaciers.

The second study by Ding et al. explores the impact of seasonally frozen ground (SFG) on rainfall infiltration and groundwater recharge in the Qinghai Lake Basin, situated in the northeastern Tibetan Plateau. Using a coupled surface-subsurface thermal hydrology model, the authors simulate the freeze-thaw dynamics and groundwater response to precipitation. Results show that SFG begins freezing in early November, reaches a depth of 2 m by late March, and completely thaws by June. During early spring rainfall events, the presence of SFG substantially reduces infiltration, resulting in delayed groundwater discharge by 1 to 3 months, depending on temperature and topography. Steeper slopes exhibited deeper ice saturation and a further 3-day delay in discharge compared to flatter slopes. The findings underscore the crucial role of permafrost and frozen ground in regulating water balance in cold, high-altitude regions, where warming may alter infiltration processes and water availability. This study adds to the understanding of hydro-ecological coupling in permafrost-influenced landscapes and has implications for predicting climate-sensitive groundwater behavior.

In the third article, Coombs et al. examine how glacier coverage, bedrock geology, and groundwater inputs influence water chemistry in glacial rivers across Alaska. By analyzing 343 water samples across seven diverse watersheds over 2 years, the study investigates the spatial and longitudinal variability in river chemistry. The findings reveal that watersheds with higher glacier coverage (e.g., Knik and Matanuska Rivers) are dominated by glacial meltwater signatures, whereas rivers like the Little Susitna are more influenced by groundwater inputs. Bedrock type significantly controls the concentrations of major and trace elements, including potentially harmful elements like arsenic (As) and uranium (U), especially in metamorphic terrains. The isotopic composition of river water also shifts downstream as tributary and groundwater contributions increase. This study provides essential insights into how glacier retreat and geological variability modulate river chemistry in cold regions. It highlights the potential risks associated with geogenic contamination in glacier-fed watersheds and offers a foundation for future water quality monitoring in changing cryospheric systems.

The fourth paper by Dar et al. investigates variability in isotopic ratios of O and H in glacier melt and snowpack across three Himalayan catchments—Lidder, Sindh, and Rambiara. The study aims to understand how environmental variables such as aspect, albedo, temperature, and elevation influence the isotopic signatures of snow and ice melt. Results indicate that aspect and temperature are dominant predictors. Solar radiation exposure on southern slopes leads to enrichment in heavy isotopes of O and H due to sublimation and partial melt whereas northern slopes show depletion in heavy isotopes with increasing altitude. The Sindh catchment displayed strong sensitivity in isotopic ratios of O and H to sampling date and thermal conditions, and the influence of albedo was particularly notable in snowpacks. The study also reports varying gradients in isotopic ratios of O and H for glacier melt vs. snowpack samples across elevation bands. These findings emphasize the importance of catchment-specific controls on the composition of stable isotope ratios of O and H, which can significantly influence hydrological modeling and water source attribution in snow- and glacier-fed basins. This research highlights the need for detailed spatial and temporal monitoring to refine our understanding of meltwater dynamics in the Himalayan cryosphere.

The research compiled under the Research Topic emphasizes how urgently multidisciplinary studies combining scientific and environmental perspectives are needed to address climate-driven changes in the cryosphere. These studies provide a critical understanding of the evolving hydro-cryosphere, particularly in the Himalayas, with parallels in regions like the Qinghai-Tibet Plateau and Alaska, and this knowledge informs sustainable water management and hazard mitigation strategies. Our knowledge of how cryospheric changes affect water security and social resilience is improved by this RT. The studies provide a solid foundation for forecasting future hydrological changes and their socioeconomic effects by tackling basic issues regarding cryospheric responses to climate variability. The findings underscore the cryosphere's role as a vital freshwater reservoir, supporting millions in agriculture, hydropower, and domestic use, while highlighting its vulnerability to warming-induced decline. The RT identifies critical research gaps, such as the need for improved modeling of cryospheric feedback in climate systems and better integration of socio-economic data to assess community vulnerability. Future studies should prioritize long-term cryospheric monitoring to capture seasonal and interannual variability, enhancing predictive models for water resource planning. Developing adaptive water governance frameworks that account for cryospheric uncertainty is essential, particularly in transboundary river basins where competing demands exacerbate tensions.

The policy implications of cryospheric change are far-reaching. Strengthening community-based adaptation, such as resilient infrastructure and diversified livelihoods, can mitigate the impacts of cryospheric decline. Investing in local stakeholders' capacity-building will enable mountain communities to adapt to shifting water dangers and availability. To ensure fair resource management across borders, international collaboration is essential for standardizing data and sharing best practices. Emerging research areas include exploring the cryosphere's role in modulating regional climate patterns and its interactions with biodiversity, which remain underexplored. Quantifying the economic costs of cryospheric loss can further guide policy prioritization. We advocate for innovative technologies, such as AI-driven forecasting, to enhance cryospheric research and hazard preparedness. These articles offer insights into hydro-cryospheric dynamics, laying a basis for sustainable strategies to address water security and climate challenges. By tackling complex environmental and societal issues in transboundary catchments, this RT paves the way for informed decision-making to safeguard cryospheric systems and ensure resilient futures for dependent communities.

Author contributions

RA: Conceptualization, Writing – review & editing, Writing – original draft, Visualization. AS: Supervision, Project administration, Visualization, Writing – review & editing. GW: Writing – review & editing, Visualization. RM: Supervision, Writing – review & editing, Project administration.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The authors declare that no Gen AI was used in the creation of this manuscript.

Publisher's note

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